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Fracture toughness assessment of ferritic–martensitic steel in liquid lead–bismuth eutectic

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ABSTRACT

The presence of micro-cracks at the surface of a ferritic–martensitic steel is known to favour its embrittlement by liquid metals and thus decrease the mechanical properties of the structural materials. Unfortunately, conventional fracture mechanics methods cannot be applied to tests in liquid metal environment due to the opaque and conducting nature of the LBE. Therefore new methods based on the normalization technique for assessment of plain strain fracture toughness in LBE were examined. This paper discusses the assessment of the plain strain fracture toughness of T91 steel in liquid lead bismuth environment at 473 K, tested at a displacement rate of 0.25 mm min^{-1} and makes the comparison with results obtained in air at the same temperature and displacement rate. Although there is a decrease of the fracture toughness by 20–30% when tested in LBE, the toughness of the T91 steel remains sufficient under the tested conditions.

1. Introduction

Liquid lead and lead bismuth eutectic have been selected as working fluids for advanced nuclear applications such as GEN IV, ADS [1,2]. The accelerator driven system (ADS) MYRRHA at the Belgian Nuclear Research Centre, SCK•CEN is designed to have liquid lead bismuth eutectic (LBE) as spallation target material as well as for primary coolant [3].

Although the risk of embrittlement of materials exposed to liquid metals has been recognized for many years, its prediction still remains problematic due to the limited knowledge of the mechanisms involved in the phenomenon. Generally, when solid metals are exposed to liquid metals and stress is applied, they may undergo abrupt brittle failure known as liquid metal embrittlement (LME). It is characterized by a premature brittle failure of an otherwise ductile material when placed in contact with specific liquid metal for the material under stress. LME is of prime interest because of the risk of damage wherever the handling of liquid metals is required. The phenomenon depends on many parameters (intensive and extensive) like metallurgical state, surface state, composition, solubility, temperature, strain rate, stress, etc. [4–6].

For the couple T91–LBE, tensile tests have not given a clear view of the embrittling behaviour of the LBE environment. It was shown by several systematic studies that embrittlement does not always occur under the same conditions [7–9]. The lack of reproducibility of tensile tests performed in LBE was attributed to the absence of wetting. To overcome this problem, relatively exotic methods such as PVD deposition of LBE after ion sputtering or chemical fluxing were used to achieve wetting [10].

However, a distinct LME effect was found without the application of wetting enhancing techniques on notched samples or samples having micro-cracks at the surface in several studies [7,8,11]. This underlined the importance of fracture toughness assessment in liquid metal environment. Unfortunately, the standard fracture mechanics approach cannot be applied to tests in liquid metal environment due to the opaque and conducting nature of the LBE. Auger et al. [12] have made an attempt to assess the fracture toughness of T91 in LBE using CCT specimens. This method is based on the visual observation of the advancing crack. The CCT sample geometry is however loaded in plane stress condition and the results are therefore more relevant for thin wall applications such as cladding tubes. Furthermore, the technique could not allow sufficient crack propagation due to shear band flow localization making it very difficult to draw reliable conclusions. Therefore, we have explored other techniques to assess plain strain fracture toughness in liquid metal environment.

This paper will show the feasibility of plain strain fracture toughness assessment of T91 in liquid metal environment based on three different normalization methods. Furthermore, the more reliable normalization method of the three was determined for the selected application and the obtained results in LBE were compared with those obtained in air.

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2. Materials

The used T91 ferritic–martensitic steel was delivered by Industeel, ArcelorMittal group as hot rolled and heat treated plates with a thickness of 15 mm. The heat treatment consisted of a normalisation treatment at 1323 K for 15 min followed by a water quench to room temperature. The tempering treatment consisted of heating the normalized steel to 1043 K for 45 min followed by air cooling to room temperature. The chemical composition of the used T91 steel is given in Table 1.

Disc-shaped CT specimens (DCT) were machined in the LT direction (see Fig. 1) and precracked in fatigue to a crack length of $a = 1/2W$, where a is the crack length and W is the width of the specimen.

The LBE material was delivered by Hetzel Metalle GmbH, Germany with a composition of 55.2 wt% Bi and 44.8 wt% Pb, 2 mg g^{-1} Cr and less than 1 mg g^{-1} Ni.

3. Method

Normalization methods were developed to allow fracture toughness assessment in aggressive environments where conventional methods cannot or hardly be applied. These methods are based on calculating the *J*–*R* curve, using only the force and displacement data recorded during the test and the initial and final crack length of the tested specimen.

Five reference tests were carried out in air. The DCT specimens were tested at a temperature of 473 K and a displacement rate of 0.25 mm min^{-1}. The crack growth during the reference tests was measured by the unloading compliance method and the potential drop method. To examine the applicability of the three normalisation methods to the used sample geometry and material type, *J*–*R* curves for these reference tests in air were also calculated by applying the three normalization methods. This approach showed the uncertainty of the obtained indirect *J*–*R* curves compared to the *J*–*R* curves obtained by online monitoring of the growing crack.

For tests in LBE, a reservoir was mounted onto the load line. Once the material had reached 473 K, the LBE was poured into the reservoir submerging the DCT specimen. The LBE reservoir was mechanically tapped on, to remove possible air bubbles. No chemical fluxing was used to promote wetting. Results by Long and Dai [13] have shown that no chemical fluxing is needed to achieve reproducible results on liquid metal embrittlement of precracked specimens due to the presence of the fatigue crack at the surface.

The test was started after the temperature settled at 473 ± 2 K for 20 min following the recommendations of standard ASTM E 1820.

For tests in LBE, no clip gauge could be used. Instead of the clip gauge data, the displacement data recorded by the test bench (stroke) had to be used. This decreases the accuracy of the *J*–*R* curve because the compliance of the entire loading line is comprised in the stroke signal in contrast with the CMOD signal which only comprises the compliance of the specimen due to the local measurement. However, this decrease in accuracy can be limited to a minimum by the application of a compliance correction to the displacement data. The compliance correction is in fact nothing more than a mathematical correction which makes every load–displacement curve of each reference test based on the CMOD signal coincides with the load–displacement curve of the same reference test based on the stroke signal.

Since the reference tests in air were performed using a clip gauge and the tests in LBE were performed on the same test bench at the same temperature, the difference between the displacement signal of the clip gauge (CMOD) and this of the test bench actuator (stroke) could be corrected for the tests in LBE without having

Table 1
Composition of the ferritic–martensitic steel T91 (wt%).

C	N	Al	Si	P	S	Ti	V	Cr	Mn	Ni	Cu	As	Nb	Mo	Sn	W
0.10	0.0442	0.015	0.22	0.021	0.0004	0.003	0.21	8.99	0.38	0.11	0.06	0.008	0.06	0.89	0.004	0.01

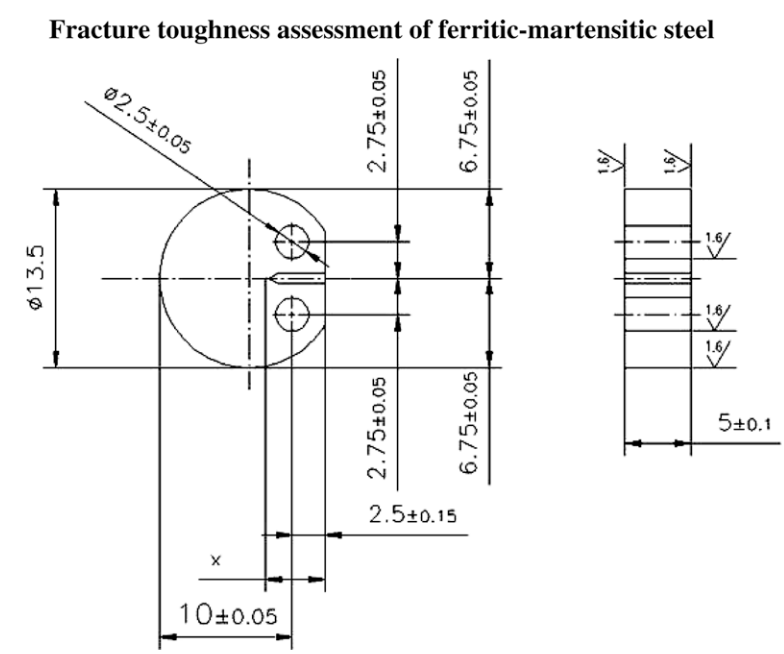

Fig. 1. Schematic representation of the disc-shaped in tension (DCT) specimen; dimensions in mm.